

Dynamics of Water Absorption and Evaporation During Methanol Droplet Combustion in Microgravity

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Presentation Outline

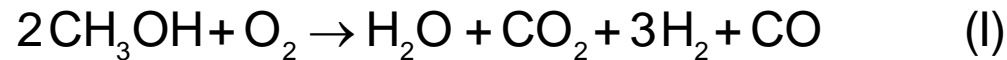
- Background
 - MeOH as a proxy fuel for droplet combustion studies
 - MeOH droplet combustion - water absorption / evaporation theory
 - Review of previous work
- Recent Analysis of ISS and Ground Tests
 - Experimental configurations
 - ... Zero Gravity Facility (ZGF) and ISS (FLEX)
 - Measurement of incipient water evaporation
 - ... LLUV camera for imaging OH* chemi-luminescence
 - ... ZGF drop rig color camera
- Future Work



Methanol as an experimental proxy fuel

Aside from obtaining a better understanding of combustion of MeOH as a fuel in practical applications, MeOH serves as an excellent experimental proxy for refining our understanding of basic combustion phenomena ...

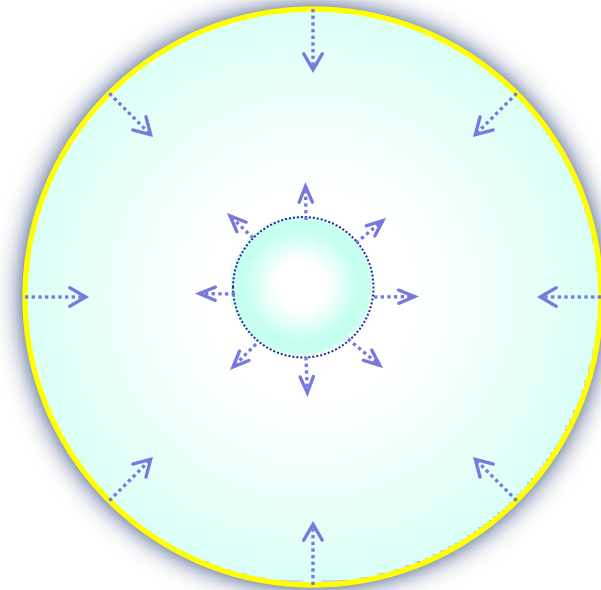
- Chemical kinetics are relatively simple ... oxidation reaction is adequately captured in a reduced 2 step mechanism (Zhang, '96)



- Only trace amounts of CH_3 resulting in very little soot production
- Stoichiometry results in relatively small flame stand-off distances ... minimizing radiative effects
- Water vapor produced from combustion diffuses back to the droplet surface, condenses ($T_b = 64.7^\circ\text{C}$) ... can serve as a useful model for studying condensed phase mixing and bi-component fuels.

MeOH Droplet Extinction Theory

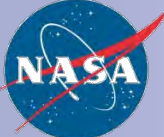
- Initially, water produced in the flame diffuses back to the droplet surface and condenses
- During the second half of the burning period the water is absorbed and gradually builds up in the droplet
- Two “idealized” limiting cases for describing the possible mixing mechanisms of the binary liquid mixture
 - **diffusion limited** ... no internal convection in the droplet resulting in a thin boundary layer of water that quickly begins to evaporate with the fuel
 - **convection limited** ... binary mixture is homogenous throughout the droplet resulting in a greater amount of water in the droplet and an increase in the concentration of water that vaporizes with the fuel
- At a certain mixture threshold water begins to evaporate with the fuel and is convected back to the flame zone
- As water reaches the flame zone the flame temperature decreases, the reaction time increases, and eventually the reaction time reaches the limit beyond which the residence time is insufficient to sustain the oxidation reaction ... **at which point the flame extinguishes**





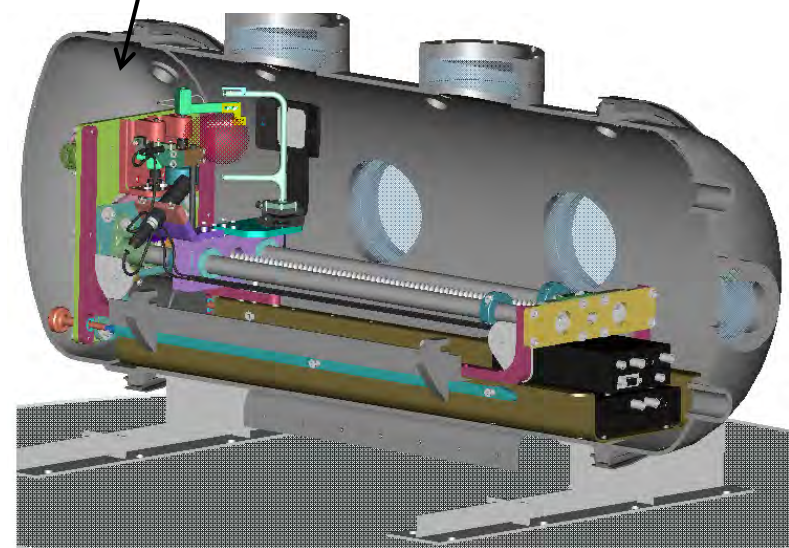
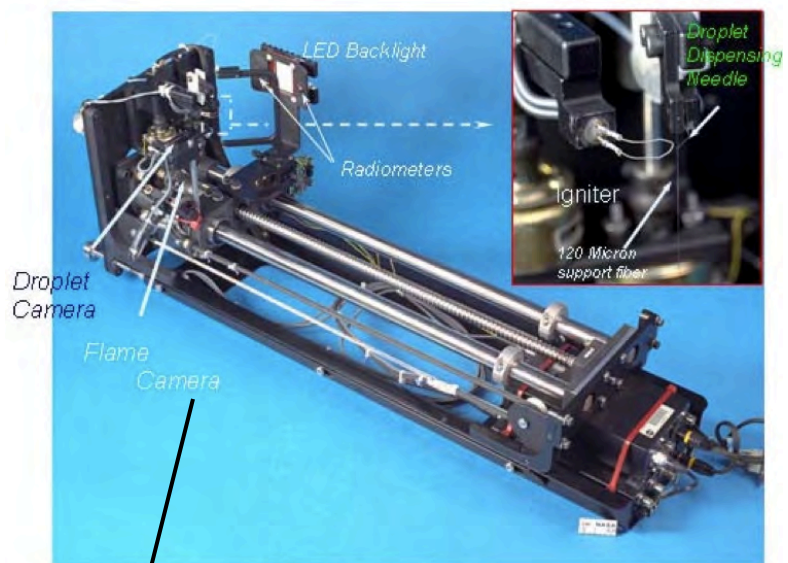
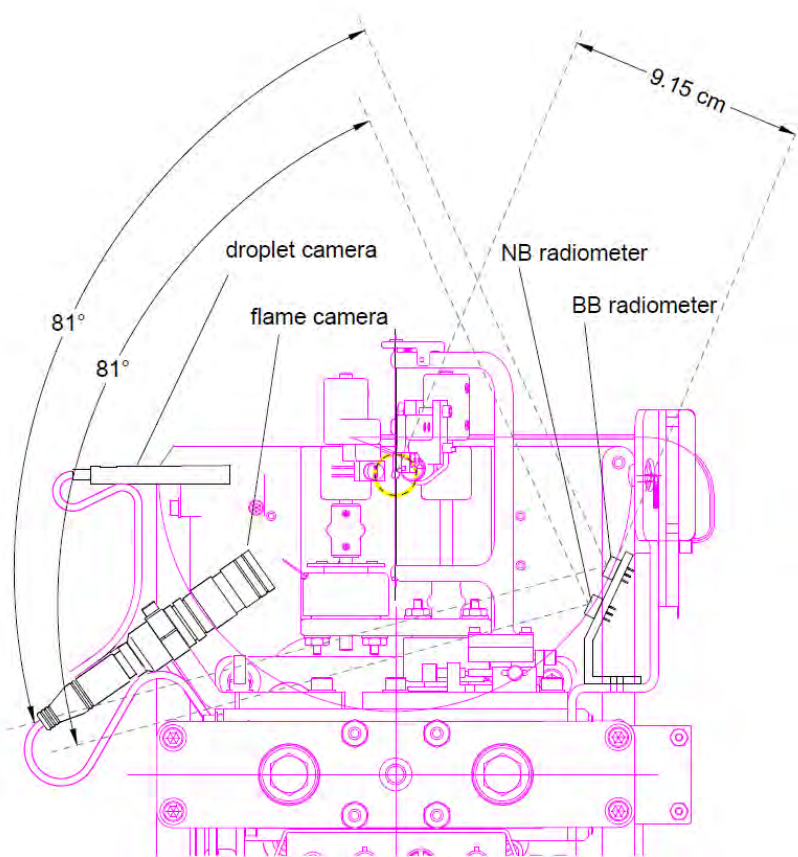
Previous Work

- Implications of water condensation on the surface of evaporating MeOH droplets first investigated in the context of a theoretical study of spray evaporation (Law & Binark, '79)
 - condensation heat release could augment evaporation rates
 - water produced from combustion could "back diffuse" to fuel surface, having a similar effect to environmental humidity
- Experiment performed on evaporation rates of suspended MeOH droplets in cold humid environments (Law et al., '87)
 - latent heat of condensation at droplet surface initially increase evaporation rates which gradually decrease as the droplet becomes concentrated with water
- The effect of water condensation and absorption at the droplet surface during rapid evaporation (e.g., combustion) first reported by Choi et al. ('88, '89) and extended in later studies (Cho et al. '90; Lee & Law, '92; Yang et al. '90; Dietrich et al., '96)
- A considerable amount of theoretical and numerical work has been performed through the years increasing our basic understanding of the complicated processes occurring during MeOH combustion – condensed phase transport, burning rate dependencies, extinction mechanisms, radiative transport, etc. (Chao et al., '90; Marchese et al., '96; Zhang et al., '96, '97, '98; Okai, et al., 2000; Dwyer et al., '96, 98, Kazakov et al., '03, Farouk et al., '12)



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ZGF Experiment Configuration





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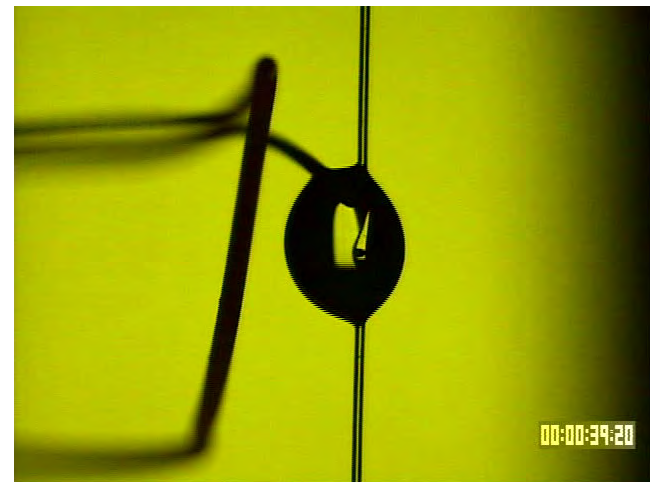
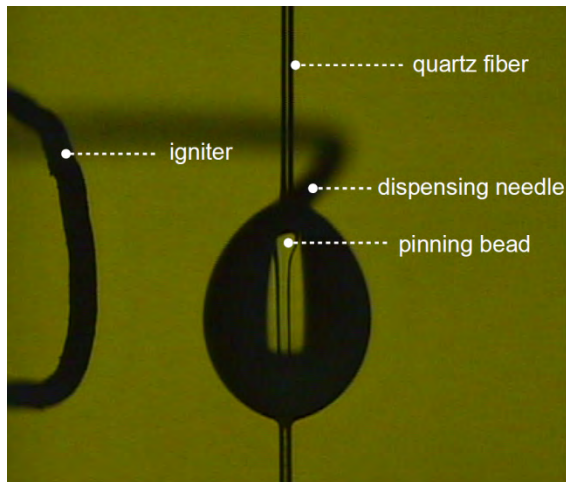
ZGF Imaging Capabilities

Test Point H-8-04

- 1.0 atm in 21% O₂ / 35% Ar / 44% N₂
- Methanol droplet
 $D_o = 1.69$ mm
 $D_{ext} = 0.79$ mm (at visible flame extinction)
- Burning rate constant, $K = 0.67$ m²/s



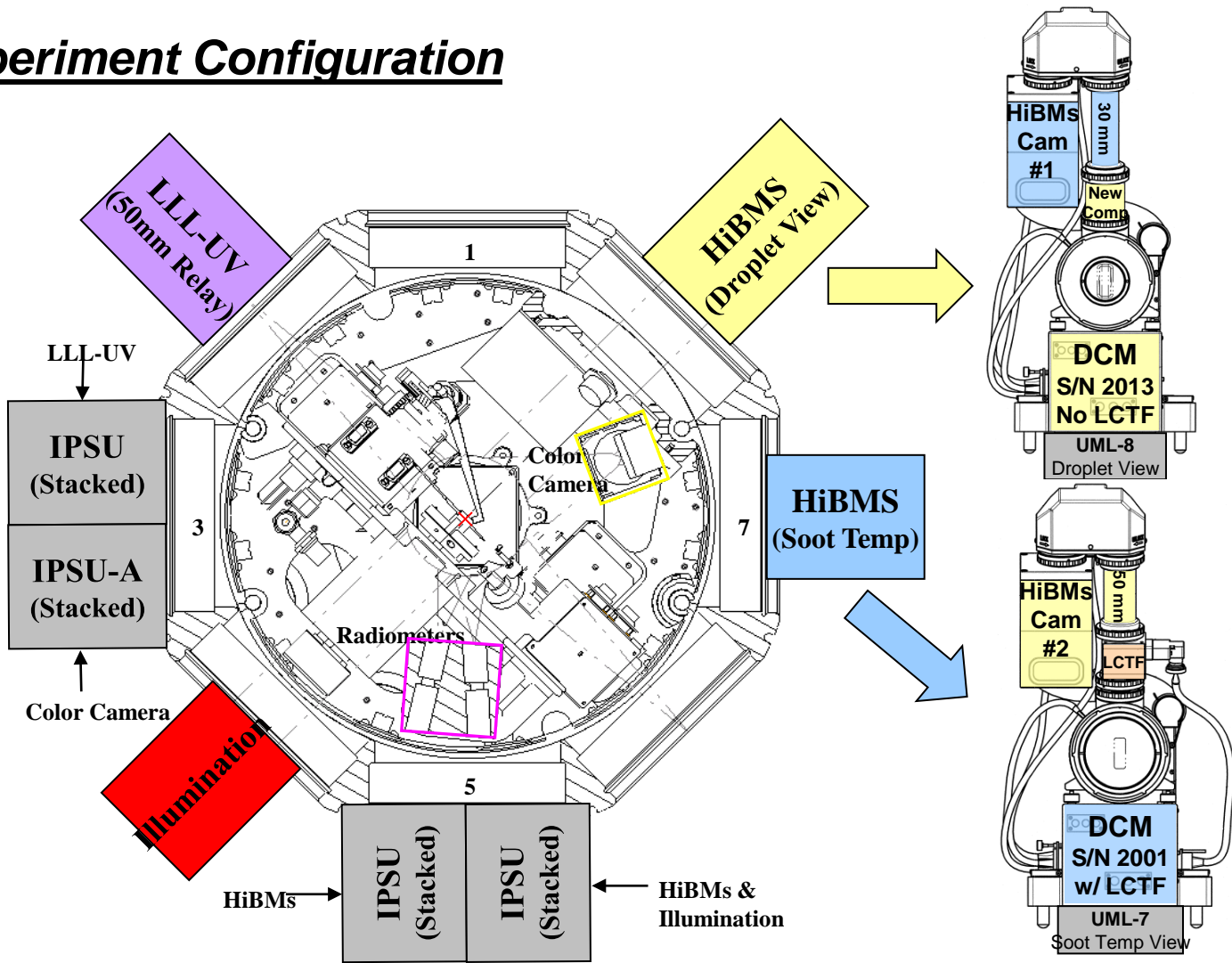
ZGF Color Camera



Backlit Droplet View



ISS Experiment Configuration



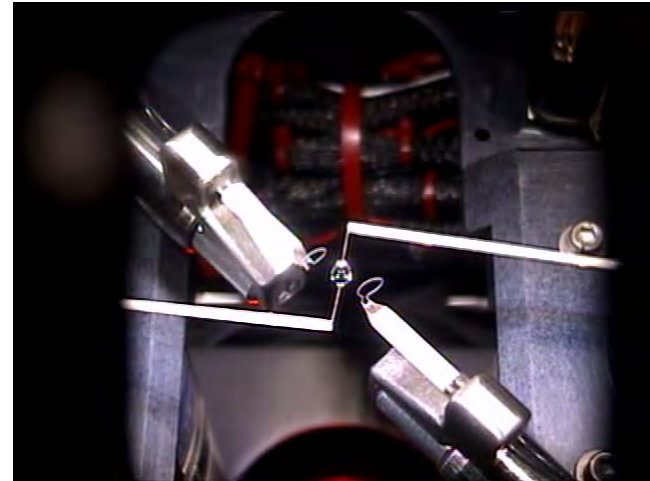


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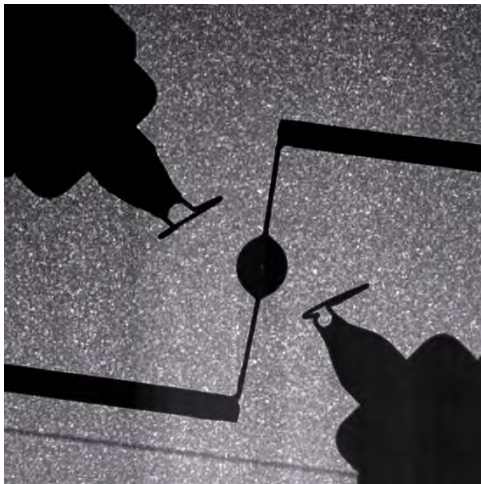
ISS Imaging Capabilities

Test Point FLEX-145

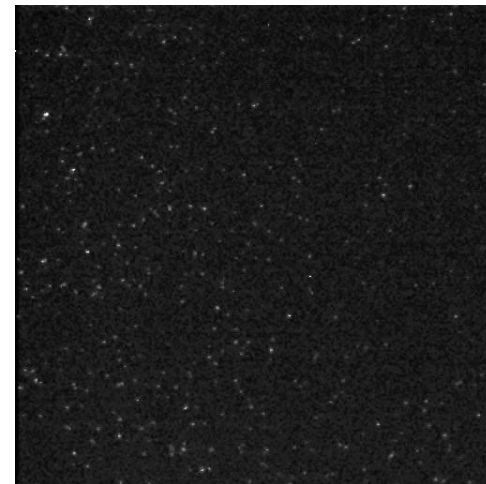
- 1.0 atm in 20% O₂ / 75% CO₂ / 5% N₂
- Methanol droplet
 $D_o = 3.38 \text{ mm}$
 $D_{ext} = 1.66$ (at visible flame extinction)
- Burning rate constant, $K = 0.44 \text{ m}^2/\text{s}$



Multit-User Droplet Combustion Apparatus (MDCA) Color Camera
used for "real time" operations monitoring and flame imaging



High Bit Multi-Spectral (HiBMS-1) Camera
used for backlit droplet image

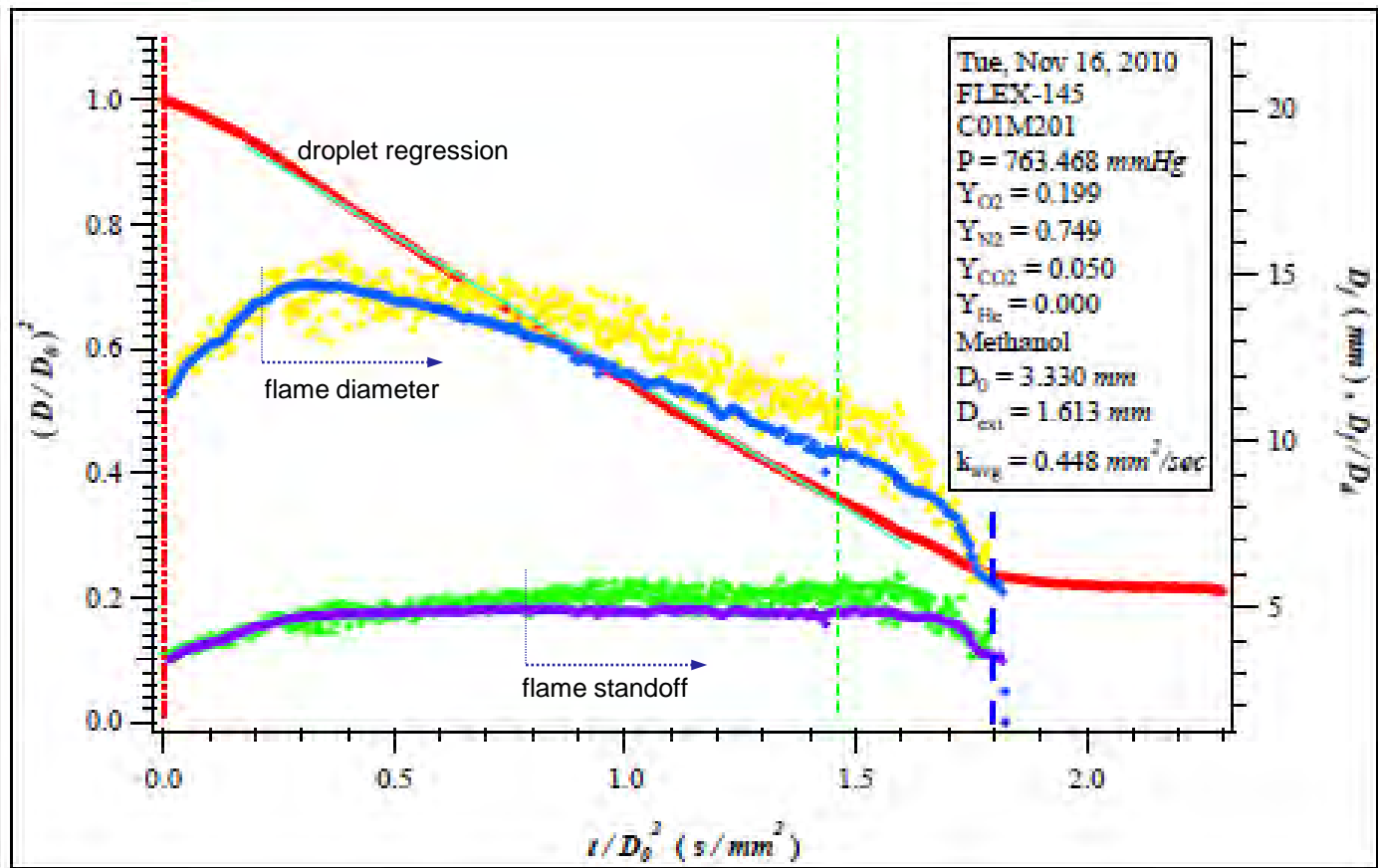


Low Light Level - Ultra Violet (LLUV) Camera
used for imaging chemiluminescence from OH* emissions



MeOH Burning History

FLEX-145 : Pressure = 1 atm , O₂ 20% / N₂ 75% / CO₂ 5% , D₀ = 3.3 mm



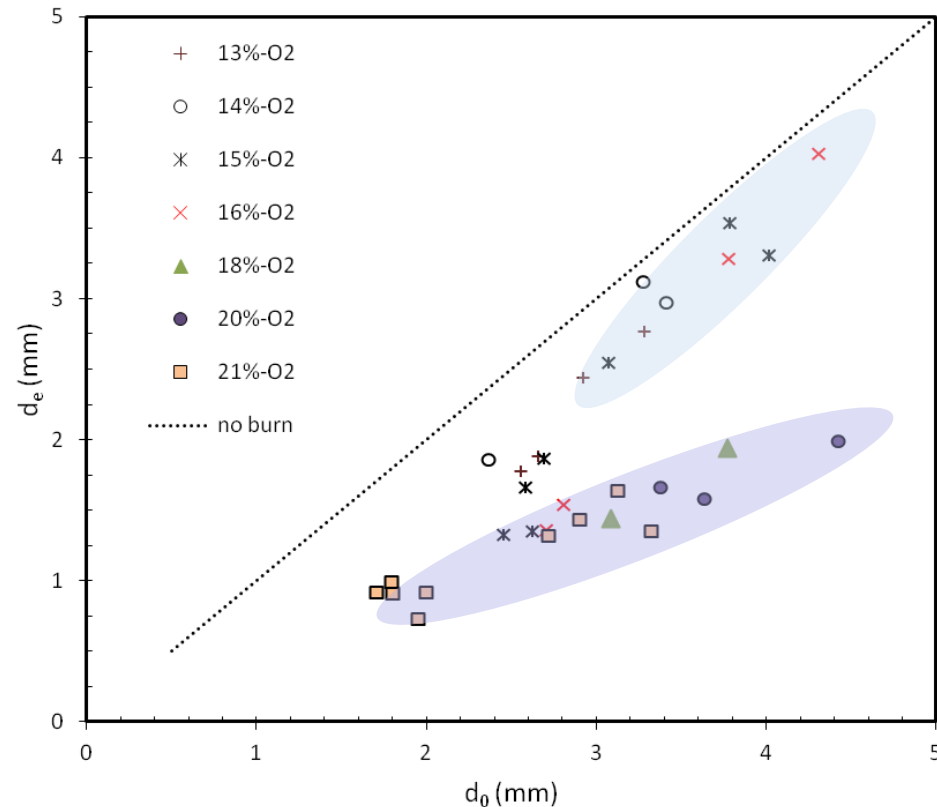
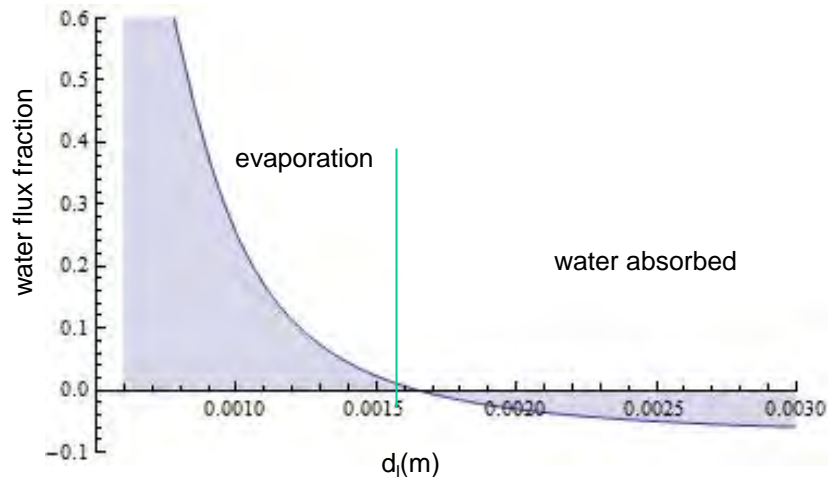
Droplet and flame histories showing progression from ignition □ early transient □ quasi-steady □ extinction.



ISS FLEX MeOH Test Results

- Recent FLEX testing with a range of O_2 concentrations from 13% to 21% w/ diluent mixtures of CO_2 / N_2 .
- Theory¹ suggests a linear relationship between extinction diameter, d_e , and initial droplet diameter, d_0

¹ B.L. Zhang, J.M. Card and F.A. Williams, *Combustion and Flame*, 1996



Extinction diameter, d_e , plotted as a function of initial diameter, d_0 , in CO_2/N_2 diluent mixtures at 1 atm pressure.

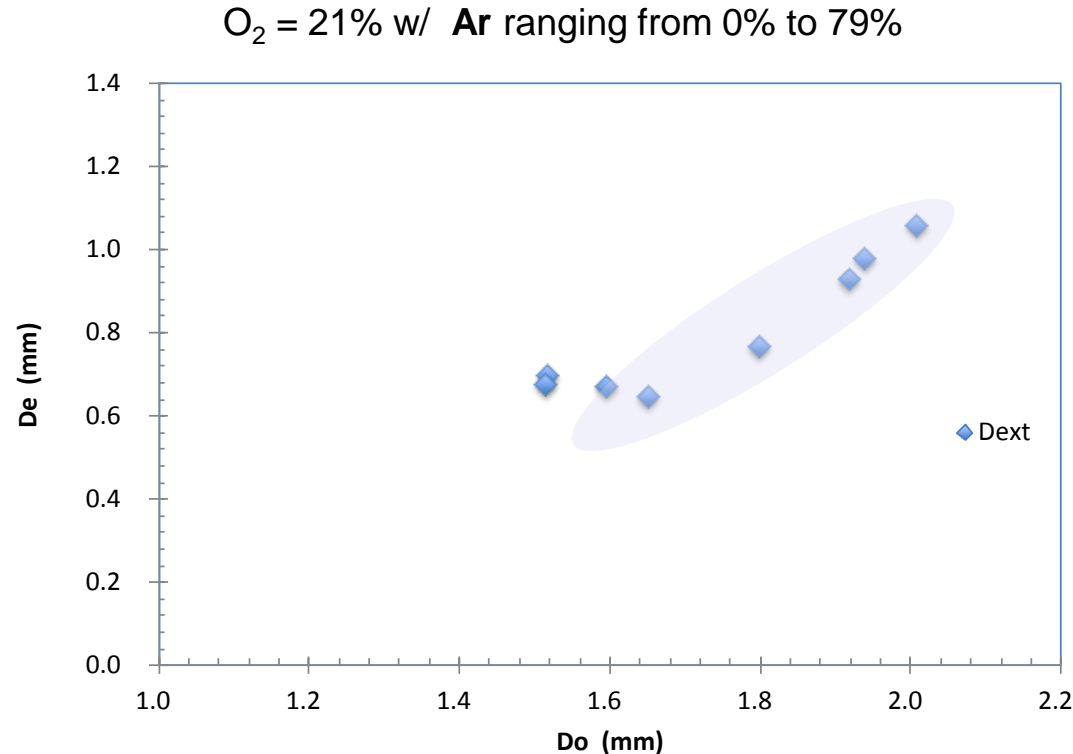


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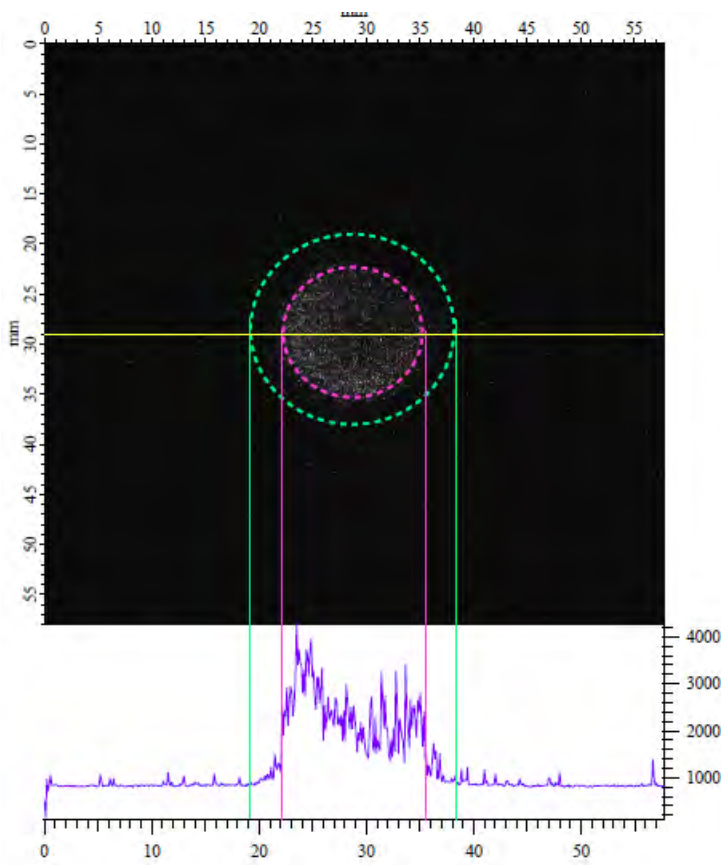
ZGF Test Results

- Similar results from tests performed in the ZGF using Ar/N₂ diluent gas mixtures
- Ar/N₂ diluent gas mixtures provide good comparisons with CO₂/N₂ diluents w/o the effects of gas phase radiation

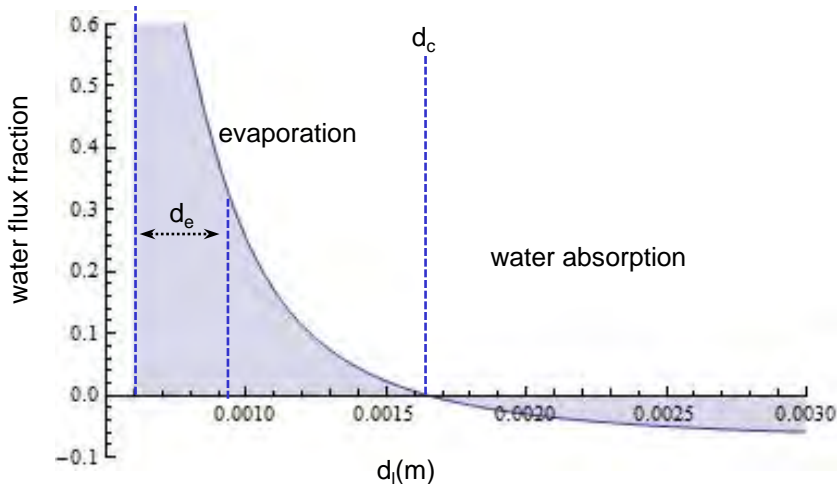
Test No.	O ₂ %	N ₂ %	Ar%	Pressure
H-7-62	21	29	50	1 atm
H-7-63	21	9	70	1 atm
H-7-65	21	9	70	1 atm
H-7-66	21	29	50	1 atm
H-7-67	21	54	25	1 atm
H-7-96	21	9	70	1 atm
H-8-02	21	0	79	.5 atm
H-8-03	21	28	51	.5 atm
H-8-04	21	44	35	1 atm
H-8-05	21	56	23	1.5 atm
H-8-07	21	16	63	1 atm
H-8-08	21	79	0	2 atm
H-8-09	21	34	45	1 atm
H-8-11	21	16	63	1 atm
H-8-12	21	54	25	1 atm
H-8-13	21	6	73	1 atm



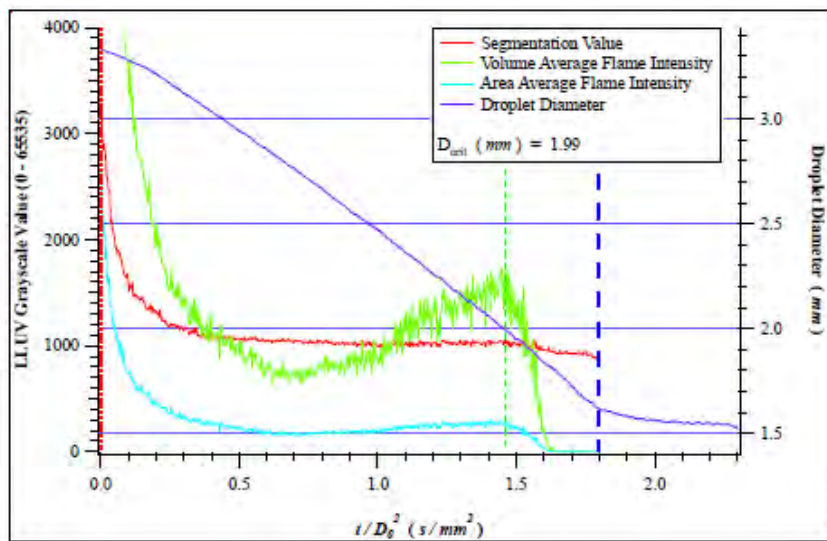
FLEX - OH* Chemiluminescence



LLUV camera OH* chemiluminescence showing a line intensity profile across the flame ... flame boundaries are the result of different intensity thresholds



water flux fraction as a function of regressing droplet

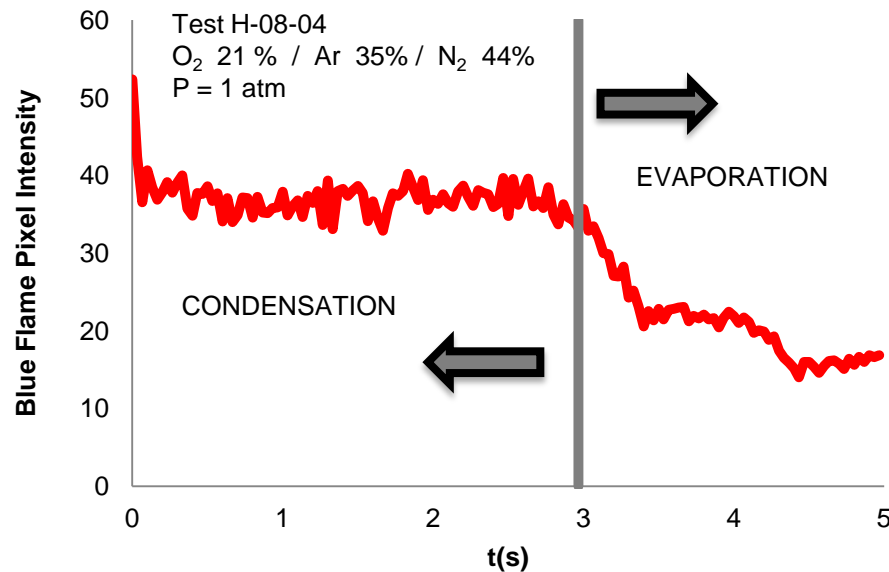


OH* chemiluminescence profile during flame history



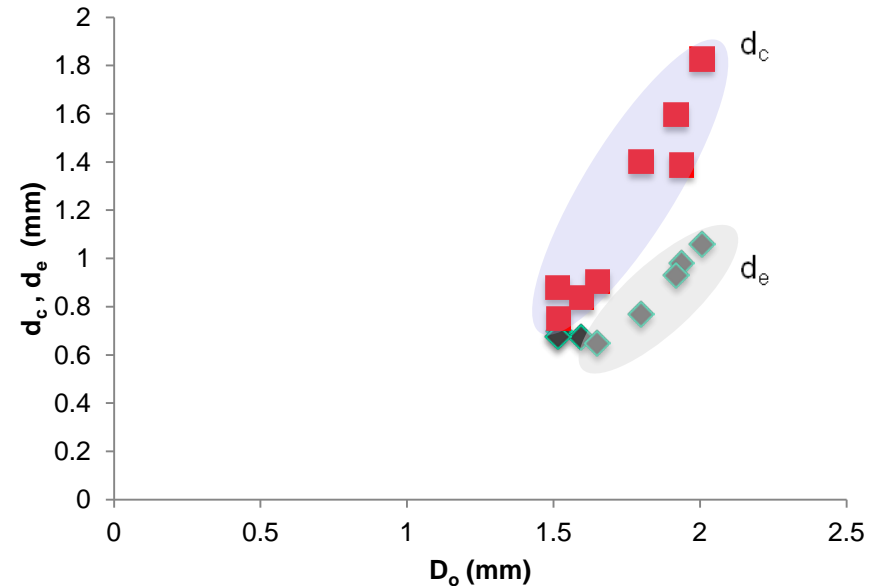
ZGF Image Analysis

- Preliminary analysis suggests that intensity measurements from ZGF 8-bit color camera may provide similar information



Flame emission intensity profile versus flame history obtained from color camera

ZGFTests - MeOH w/ 21% O_2 and Ar / N_2 diluent mixtures



Plot of d_c (point of water flux transition) and d_e (extinction diameter) as a function of initial droplet diameter, d_0 , using information from 8 bit color camera from ZGF drop rig.



Summary

- Flame intensity measurements using OH* chemiluminescence images from the FLEX LLUV camera provide information of the water flux transition point in MeOH droplet combustion studies
- Similar analysis using a simple color camera may provide reasonable approximation of the same phenomena

Future work

- Extend image analysis technique to full range of FLEX MeOH experimental data
- Refine image analyses techniques for correlation with water flux transition point
- Compare experimental results with theory